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CASE STUDY • MAGNESIUM PRODUCTION

Life cycle assessment of primary magnesium production using the Pidgeon process in China

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Abstract
Background, aims, and scope China has been the largest primary magnesium producer in the world since year 2000 and is an important part of the global magnesium supply chain. Almost all of the primary magnesium in China is produced using the Pidgeon process invented in the 1940s in Canada. The environmental problems of the primary magnesium production with the Pidgeon process have already attracted much attention of the local government and enterprises. The main purposes of this research are to investigate the environmental impacts of magnesium production and to determine the accumulative environmental performances of three different scenarios. System boundary included the cradle-to-gate life cycle of magnesium production, including dolomite ore extraction, ferrosilicon production, the Pidgeon process, transportation of materials, and emissions from thermal power plant. The life cycle assessment (LCA) case study was performed on three different fuel use scenarios from coal as the overall fuel to two kinds of gaseous fuels, the producer gas and coke oven gas. The burden use of gaseous fuels was also considered.
Methods The procedures, details, and results obtained are based on the application of the existing international standards of LCA, i.e., the ISO 14040. Depletion of abiotic resources, global warming, acidification, and human toxicity were adopted as the midpoint impact categories developed by the problem-oriented approach of CML to estimate the characterized results of the case study. The local characterization and normalization factors of abiotic resources were used to calculate abiotic depletion potential (ADP). The analytic hierarchy process was used to determine the weight factors. Using the Umberto version 4.0, the emissions of dolomite ore extraction were estimated and the transportation models of the three scenarios were designed.
Results and conclusions The emissions inventory showed that both the Pidgeon process of magnesium production and the Fe–Si production were mainly to blame for the total pollutant emissions in the life cycle of magnesium production. The characterized results indicated that ADP, acidification potential, and human toxicity potential decreased cumulatively from scenarios 1 to 3, with the exception of global warming potential. The final single scores indicated that the accumulative environmental performance of scenario 3 was the best compared with scenarios 1 and 2. The impact of abiotic resources depletion deserves more attention although the types and the amount of mineral resources for Mg production are abundant in China. This study suggested that producer gas was an alternative fuel for magnesium production rather than the coal burned directly in areas where the cost of oven gas-produced coke is high. The utilization of "clean" energy and the reduction of greenhouse gases and acidic gases emission were the main goals of the technological improvements and cleaner production of the magnesium industry in China.
Recommendation and perspective This paper has demonstrated that the theory and method of LCA are actually helpful for the research on the accumulative environmental performance of primary magnesium production. Further studies with "cradle-to-cradle" scheme are recommended. Furthermore, other energy sources used in magnesium production and the cost of energy production could be treated in further research.

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1 Introduction

China is among the global countries that are richest in magnesium, whose major raw materials of the magnesium industry come from the resources of magnesite, dolomite, lake brines, and seawater (Chen and Shi 1995). Compared with other structural materials, magnesium and magnesium alloys boast a number of advantages (Mordike and Ebert 2001), such as low density, high specific strength, good thermoformability, and high performance of electromagnetic shielding, and these outstanding features would make them possess both significant application value and broad application prospects. In the field of transportation, the materials of magnesium and magnesium alloys could meet the requirements of weight loss, energy saving, and being environment friendly in the automobile industry (Liu et al. 1999); for the structural parts of the shell of mobile communications and portable computers and others, they could replace engineering plastics so as to satisfy the requirements of making the products light, thin, small, and highly integrated (Liu 2003).

Since the 1990s, a rapid increase in production of primary magnesium has been seen in China and became the domestic fifth major nonferrous metal after aluminum, copper, lead, and zinc (Editorial Board of the Yearbook of Nonferrous Metals Industry of China 2005). Primary magnesium production ability reached 816,000 tons during the year 2005, and the production of primary magnesium reached 468,000 tons which is 2.4 times of the output in 2000 (Table 1); meanwhile, its export volume stayed at 353,000 tons, accounting for 75% of the global market share (Meng 2006). China is the largest primary magnesium producer in the world, and the Pidgeon process invented in 1940s in Canada is an important technique to produce primary magnesium in China. Magnesium production with the Pidgeon process boasts the advantages of short technical process, low investment input, quick completion of workshop, and low production cost, but the process was resource- and energy-intensive and leads to relatively severe environment pollution, and the emissions of the air pollutants resulting from the energy consumption in particular have already attracted much attention of the local government and enterprises.

Table 1 The output of primary Mg production in China and the world

Year	2000	2001	2002	2003	2004	2005
China (10^3 tons)	195	216	268	354	450	468
World (10^3 tons)[a]	479	448	468	544	655	667
Contribution of China (%)	40.7	48.2	57.3	65.1	68.7	70.2

[a] From http://www.intlmag.org/files/yend2005.pdf

At present, the international life cycle assessment (LCA) research on both the production of primary magnesium and the magnesium products is still at its initial stage, and it is not yet clear what the impacts are on the extensive use of magnesium products in the environment. A cradle-to-gate life cycle study was conducted using averaged data for magnesium production in China to calculate the global warming impact of Chinese magnesium ingots (Ramakrishnan and Koltun 2004). Following the ISO 14040 (ISO 14040 2006), the goal and scope definition, life cycle inventory analysis, and life cycle impact assessment, environmental assessment on the cradle-to-gate life cycle of primary magnesium production using the Pidgeon process in present China will be carried out as well as the accumulative environmental performance of different fuels used in different scenarios and the characterization results, including abiotic depletion potential (ADP) of resources, global warming potential (GWP), acidification potential (AP), and human toxicity potential (HTP) will be compared in this article.

2 The case study

2.1 Introduction of the Pidgeon process

The main process of primary magnesium production with regard to the method of mining, dolomite calcination, batch pelletizing, reduction, refinement, and ingot casting consists of five steps. Materials consumption usually includes dolomite, ferrosilicon, and fluorite. The dolomite ore, which is mined and transported to a magnesium plant, is calcined in rotary or vertical furnaces at about 1,200°C, which is called calcination step. The calcining process yields dolime, as given by the following reaction:

$$(CaCO_3 \cdot MgCO_3)_{(s)} + heat \rightarrow (CaO \cdot MgO)_{(s)} + 2CO_{2(g)} \tag{1}$$

The dolime mixed with ferrosilicon containing above 75% of silicon as reduction agent and fluorite containing around 95% of CaF_2 as catalyst after calculating and measuring ingredients is ground. Then, these three kinds of materials were placed inside the reduction pots after being compressed into balls by a pelleter and heated to 1,200°C, subsequently drawing the air from the reduction pots at a vacuum of 13.3 Pa or higher, and the magnesium vapor appears after the reduction reaction. Magnesium vapor

sublimates crystal magnesium in the condenser in the front part of reduction pots. The reaction (Toguri and Pidgeon 1962) describing the reduction process is as follows:

$$2(\mathrm{CaO}\cdot\mathrm{MgO})_{(s)}+\mathrm{Si(Fe)}_{(s)}\rightarrow 2\mathrm{Mg}_{(g)}+(2\mathrm{CaO}\cdot\mathrm{SiO_2})_{(s)}+\mathrm{Fe}_{(s)} \tag{2}$$

The crystal magnesium, also called Mg crowns, still contains certain amounts of impurities. The last step of the Pidgeon process is the refining, where the Mg crowns are melted and treated with purifying agents. The surface of melted magnesium needs to be blanketed with an appropriate flux or cover gas preventing oxidation, because the melted magnesium is highly combustible, thus causing serious safety problems. The molten magnesium is then transferred from the melting furnace and poured into ingot molds to produce magnesium ingots.

2.2 Introduction of ferrosilicon production

Ferrosilicon, mainly produced in a ferroalloy plant in China, is an important material for magnesium production using the Pidgeon process. Typical usage of the material could be 1.08–1.2 tons of ferrosilicon per ton of magnesium. In China, ferrosilicon is produced using iron oxide and silica as raw materials and coke as reduction agent with an energy-intensive electric arc furnace that may use 8,400 kWh of electrical energy per ton of ferrosilicon (Hauksdóttir et al. 2002; Zhou 2001).

The chemical equations describing ferrosilicon production are shown below:

$$\mathrm{Fe_2O_3}+4\mathrm{SiO_2}+11\mathrm{C}\rightarrow 2\mathrm{FeSi_2}+11\mathrm{CO}_{(g)} \tag{3}$$

The ferrosilicon needs to be transported to magnesium plants over longer distances. Details of the transportation from ferrosilicon manufacturers to magnesium plants will be introduced in Section 4.4.

2.3 Case scenarios

Primary magnesium production with the Pidgeon process is resource- and energy-intensive, and the gaseous emissions emitted from the fuel combustion process in particular cause severe environment pollution. For this reason, technology improvement, energy conservation, and emission reduction become the fundamental methods of achieving sustainable development of the magnesium industry in China. Currently, domestic magnesium enterprises are also active in reducing consumption and saving energy through technology improvement. The utilization of gas, such as producer gas (PG) and coke oven gas (COG) produced from coal, was seen as a new technology standard, when we surveyed the companies with the highest primary Mg production capacity in China.

In order to show some effects of implementing gaseous fuels, this article, based on the domestic practices of magnesium production, will compare the environmental impacts caused by coal and the two different types of fuels, PG and COG, used in the process. For the purpose of comparability, companies with similar production scale and capacity as well as arts and crafts were chosen. Most of the processes calculated in our life cycle model represent conditions of present China.

Respective introductions of the current three scenarios of the primary magnesium production were as follows:

- Scenario 1: Factories using the Pidgeon process were located in provinces that were relatively rich in dolomite ore, and they basically produced using local dolomite resources. Ferrosilicon and fluorite need to be transported over long distances to magnesium plants. Coal was the overall fuel used in the process.
- Scenario 2: Some of the factories still use coal in addition to PG, mainly because of operational issues in the calcination step. The major fuels used in the process were listed in Table 2. The rest was identical to scenario 1.

PG is produced in a furnace or generator in which air and steam are forced upward through a bed of burning fuel of coal. The carbon of the fuel is oxidized by oxygen of air from below to form carbon monoxide. The nitrogen of air, being inert, passes through the fire without change. When steam is introduced with the air, the final gaseous product also contains hydrogen (Ramana et al. 2005). The reactions describing the process are as follows:

$$\mathrm{C}+\mathrm{CO_2}=2\mathrm{CO}-162.4\ \mathrm{MJ/kmol} \tag{4}$$

$$\mathrm{C}+\mathrm{H_2O}=\mathrm{CO}+\mathrm{H_2}-118.8\ \mathrm{MJ/kmol} \tag{5}$$

The generator in China has such advantages as simple equipment, easy operation, and low investment input. The gaseous sulfide, nitride, and particulates can be easily and efficiently eliminated before PG used, so it has better

Table 2 Inventory of main resources and energy consumption of the three scenarios

Inputs	Unit	Scenario 1	Scenario 2	Scenario 3
Dolomite	kg/ton (Mg)	1.50E+04	1.05E+04	1.00E+04
Ferrosilicon	kg/ton (Mg)	1.20E+03	1.10E+03	1.08E+03
Fluorite	kg/ton (Mg)	2.48E+02	1.81E+02	1.74E+02
Coal	kg/ton (Mg)	1.19E+04	3.36E+03	2.28E+03
PG	m^3/ton (Mg)	0	3.14E+04	0
COG	m^3/ton (Mg)	0	0	6.42E+03
Electric power	kWh/ton (Mg)	1.00E+03	1.10E+03	1.00E+03

environmental characteristics than coal (Wu and Chen 2001). PG, of which calorific value varies in the range of 4.6–7.5 MJ/m^3, is a mixture of approximately 26% carbon monoxide (CO), 51% nitrogen(N_2), 14% hydrogen (H_2), and 9% other gases such as CO_2, CH_4, and CmHn.

- Scenario 3: An associated enterprise represents a sort of production networks combining coke production, ferrosilicon production, and magnesium plants. The factories were relatively concentrated, and distances of ferrosilicon transport are less than 5 km. Coke production, which is needed for the making of ferrosilicon, comes along with the by-product of a considerable amount of COG which can be used for the major fuel of magnesium production, with the merits of high calorific value, being at 17.354 MJ/m^3, and convenient combustion. For the Mg plants, most of the overall fuel consumption is achieved by implementing waste heat of coke production. After separating the ammonia and crude benzene, the main ingredients within the gas consists of hydrogen (H_2), methane (CH_4), carbon monoxide (CO), etc (Bisio and Rubatto 2000).

Comparing petroleum and natural gas, China enjoys rich and widespread coal resources as well as relatively low price in coal, so the major fuel of magnesium production was coal. Lower calorific value and operational issues of PG and limitations on gas supply conditions for COG make them unable to totally replace coal powder at present, so the process of magnesium production adopts the mode of co-firing coal powder and gas.

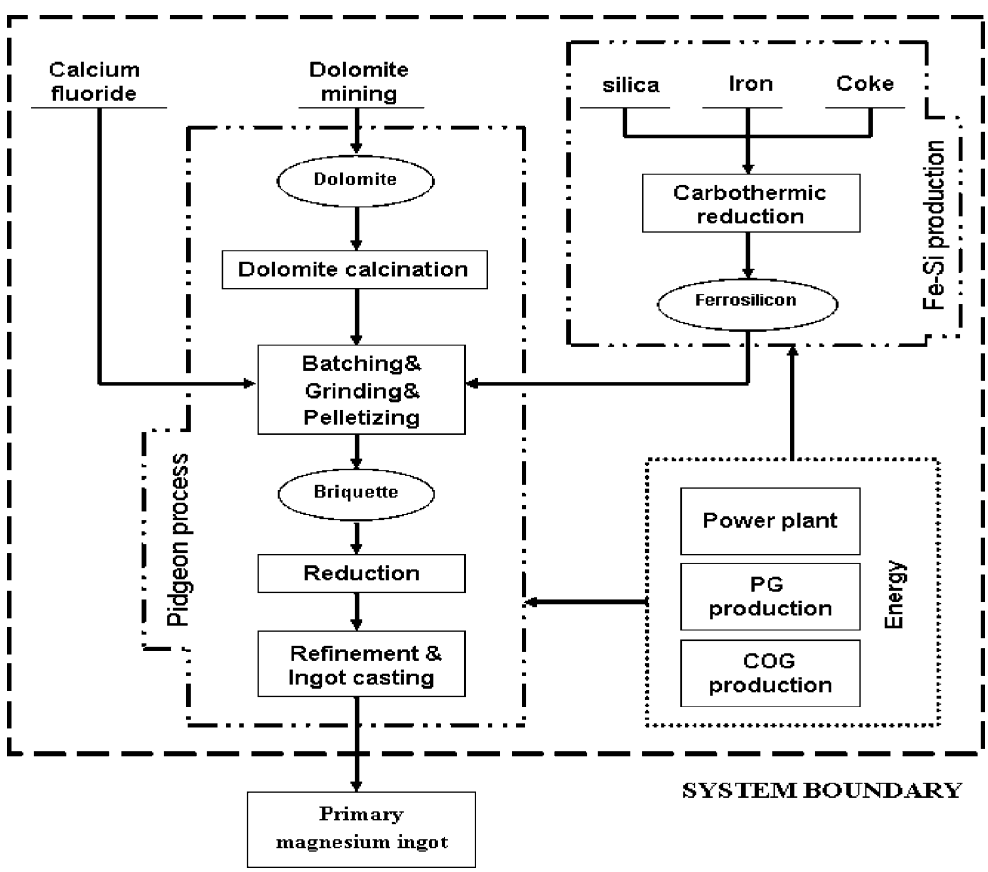
3 Goal and scope definition

This article sets the functional unit as 1 ton of magnesium ingots. The primary objectives of this article were as follows:

1. Display quantitatively the environmental load and compare the differences of the environmental impacts of magnesium production stages.
2. Illustrate the accumulative environmental performances of magnesium production with the alternative fuel scenarios and provide a suggestion about energy use strategy.

Based on the scope of the LCA, the system boundary was illustrated in Fig. 1. The Pidgeon process can be subdivided into four steps: dolomite calcinations, batch pelletizing, reduction and refinement, and ingot casting. Auxiliary subsystems include dolomite mining, ferrosilicon production and transportation of involved materials such as ferrosilicon and calcium fluoride, and the gaseous fuels production and power plant-supplied energy to the processes.

Fig. 1 System boundary of LCA for magnesium production using the Pidgeon process



4 Life cycle inventory

4.1 Data collection of the main processes

Data were collected, in part, through interviews and site visits at local enterprises recommended by the China Magnesium Association (CMA) as representative of the Pidgeon process with the highest primary Mg production capacity in China, located in Shanxi Province. A consistent set of data on energy consumption and material inputs was obtained by sending them a standardized questionnaire. The inventory data of the three scenarios listed in Table 2 showed the average level, based on our survey, of all processes with the same function.

Primary magnesium production consists of many processes; therefore, it is difficult to gather information from factories regarding all the parts. We have focused on compiling the life cycle inventory (LCI) data on the most important processes, specifically the Pidgeon process and ferrosilicon production. In addition, in the few processes in which the data found were not sufficiently reliable, quasi-process information from commercial database of Umberto software (Institut für Umweltinformatik 2001) has been used.

Air pollutants, among the wastes produced in magnesium production using the Pidgeon process, caused the most serious impact on the environment. The major waste gases produced in the processes included CO_2, CH_4, SO_2, NO_X, HF, and particulates (PM10). Fresh water, used in small amounts in the process of magnesium production, is used as a cooling agent often with recirculation through a cooling tower. Waste water is subsequently discharged from the water treatment plant where suspended solids and oil/grease are monitored. Data on liquid emissions are unavailable because they are beyond the control of primary magnesium producers, and the impact of liquid waste will not be taken into consideration. Bulk solid waste mainly consists of calcium oxide and silicon dioxide which may become toxic at low levels to human beings and the environment, of which environmental impact could be ignored.

4.2 Dolomite mining

Dolomite is the major raw material in magnesium production using the Pidgeon process. Domestic dolomite reserves required in magnesium production are very rich, and mineral resources are found all over the country. Ensured reserves stayed at above 230 million tons by the end of 2000 (Wang 2002), and the proportion of MgO in dolomite ore is usually around 20%. All data on dolomite mining were obtained from the Umberto (version 4.0) database.

4.3 Emissions from energy production

Comparison of energy use, as addressed in our study, is of special interest, and there is an obvious burden use of alternative fuels from using coal to running the process with gaseous fuels. The specific factors on COG production were obtained from the average data of different plants in China (Yang et al. 2002). Data from producer gas production, surveyed from the plants, were converted into air pollution emission factors by the Umberto software.

The electric power used in Mg production was mainly supplied by a national power grid. The emission factors of power plants were obtained from the data based on the situation of China (Di et al. 2005, 2007). The atmospheric emissions, associated with the Pidgeon process, from power plants include only the pollutants mentioned above.

Considering the Pidgeon process is relatively independent from Fe–Si production, and the emissions from electricity consumed in Fe–Si production were calculated and integrated into the ferrosilicon process to show its whole portrait. Also, the inventories of power plant shown in Table 3 presented the emissions from electricity using the Pidgeon process.

4.4 Transportation

Transport processes included the impact of emissions caused by materials such as dolomite, ferrosilicon, and fluorite transported to Mg plants. The “tkm” has been assumed as a functional unit for transport, which is the transport of 1,000-kg goods over 1 km. The transportation models, based on the record of the journey of survey in the three scenarios, were designed by the Umberto software. Transportation including railway and road is as follows:

- From dolomite mine to magnesium production plants: Domestic factories using the Pidgeon process have easy access to local resources for production. The average distance, in the three scenarios, from the dolomite mine to the magnesium plant was assumed to be 50 km, and duty trucks with a net load of 15 tons would be used for the transport.
- From ferrosilicon plants to magnesium plants: In both scenarios 1 and 2, ferrosilicon plants were far from the magnesium-smelting plants. Assuming their average distance was 200 km, duty trucks with a net load of 20 tons would be used for the transport. In scenario 3, the ferrosilicon plant was in close distance with magnesium plants. Therefore, assuming their average transportation distance was 5 km, duty trucks with a net load of 4 tons would be used.
- Transportation of fluorite: Taking major producing areas of fluorite into consideration, both railway and

Table 3 Life cycle emissions inventory of the three scenarios

	Emissions	CO_2 (kg/ton Mg)	SO_2 (kg/ton Mg)	NO_X (kg/ton Mg)	CH_4 (kg/ton Mg)	HF (kg/ton Mg)	PM10 (kg/ton Mg)
Scenario 1	Mining	5.85E+01	9.84E−02	4.92E−02	7.03E−02	0	1.08E+03
	Fe–Si production	7.70E+03	5.35E+01	4.58E+01	2.38E+01	0	4.84E+01
	Pidgeon process	2.74E+04	8.07E+01	8.94E+01	2.49E+00	3.44E+01	2.77E+02
	Power plant	7.62E+02	4.34E+00	4.54E+00	2.30E+00	0	1.90E+00
	Transportation	1.09E+02	3.09E−02	1.17E+00	3.55E−03	0	5.55E−02
	Total	3.60E+04	1.39E+02	1.41E+02	2.87E+01	3.44E+01	1.41E+03
Scenario 2	Mining	4.09E+01	6.89E−02	3.44E−02	4.92E−02	0	7.56E+02
	Fe–Si production	7.06E+03	4.90E+01	4.20E+01	2.13E+01	0	4.44E+01
	Pidgeon process	2.83E+04	7.95E+01	5.51E+01	0	2.51E+01	9.44E+01
	Power plant	8.38E+02	4.77E+00	4.99E+00	2.53E+00	0	2.09E+00
	PG production	3.49E+03	4.65E+00	3.05E+00	7.66E+01	0	1.15E+01
	Transportation	8.06E+01	2.29E−02	8.65E−01	2.61E−03	0	4.14E−02
	Total	3.98E+04	1.38E+02	1.06E+02	1.00E+02	2.51E+01	9.08E+02
Scenario 3	Mining	3.90E+01	6.56E−02	3.28E−02	4.69E−02	0	7.20E+02
	Fe–Si production	6.93E+03	4.81E+01	4.12E+01	2.09E+01	0	4.36E+01
	Pidgeon process	2.06E+04	7.32E+01	2.32E+01	0	2.41E+01	6.46E+01
	Power plant	7.62E+02	4.34E+00	4.54E+00	2.30E+00	0	1.90E+00
	COG production	3.84E+03	3.38E+00	1.25E+00	6.61E+01	0	4.23E+00
	Transportation	6.06E+01	1.72E−02	6.58E−01	2.09E−03	0	3.00E−02
	Total	3.22E+04	1.29E+02	7.09E+01	8.93E+01	2.41E+01	8.34E+02

road transportations were used. Assuming that the average transportation distance for railway transportation with diesel engine as major force was 1,000 km, and for road transportation 50 km, duty trucks with a net load of 15 tons would used for the transport.

5 Impact assessment

The problem-oriented approach (Guinée et al. 2001), developed by the Institute of Environmental Sciences (CML) of Leiden University, was used in this study. The midpoint impact categories considered were: depletion of abiotic resources, climate change, acidification, and human toxicity. Given the scope of the case study and relevant LCI, the results for the other impact categories such as ozone depletion, eutrophication, etc. are all zero. Therefore, they are omitted from the LCIA indicators. The impact assessment method consists of three steps: characterization, normalization, and weighting.

5.1 Characterization and normalization

The environmental impact category, characterization factors, and the corresponding natural resources or substances were listed in Table 4. The characterization factors of GWP, AP, and HTP for the emissions were taken from literature (Guinée et al. 2001). The characterization factors calculated based on the data of mineral ensured reserves and extraction rate in China (Gao et al. 2009) were used to estimate the abiotic resource depletion potential. The "antimony" was chosen as a reference.

The normalization factors (world, mid-1995) of GWP, AP, and HTP were taken from literature (Guinée et al. 2001), while the normalized value of abiotic resources depletion was based on the situation of China in 2004, which is 2.14×10^{10} kg antimony equivalent. The regional distribution of abiotic resources as well as the roles that all kinds of resources play in the economic development differs between regions, but the local total base reserves from ore should be used to obtain equivalency characterization factors for abiotic resource categories, especially adopted in the assessment of a certain material production (Gao et al. 2009), in place of ultimate reserves.

5.2 Weighting

In the final stage, the normalized results were multiplied by a weighting factor representing the relative importance of the total environmental impact. It enabled an overall comparison of the three scenarios. The analytic hierarchy process, a matrix-based approach measuring impact priorities in a hierarchical structure (Ong et al. 2001; Saaty 1980), was used to determine the weight factors. The

Table 4 Environmental impact category, characterization factors, and the corresponding substances

Impact category	Indicator [units]	Parameter
Depletion of abiotic resources	ADP [kg antimony eq]	Dolomite, fluorite, silica, iron, coal, crude oil, natural gas
Climate change	GWP_{100} [kg CO_2 eq]	CO_2, CH_4
Acidification	AP [kg SO_2 eq]	SO_2, NO_X, HF
Human toxicity	HTP_{100} [kg 1,4-DCB eq]	SO_2, NO_X, HF, PM10

relevant quantified judgment on the impacts was represented by a 4×4 matrix. Matrix A was as follows:

$$A = \begin{array}{c} \\ \text{GWP} \\ \text{AP} \\ \text{HTP} \\ \text{ADP} \end{array} \begin{array}{c} \begin{array}{cccc} \text{GWP} & \text{AP} & \text{HTP} & \text{ADP} \end{array} \\ \begin{bmatrix} 1 & 2 & 3 & 5 \\ 1/2 & 1 & 2 & 3 \\ 1/3 & 1/2 & 1 & 2 \\ 1/5 & 1/3 & 1/2 & 1 \end{bmatrix} \end{array}$$

Then, the vector of priorities, deviation from consistency, and principle eigenvalue were determined, and the consistency testing showed that the results have a very high consistency. The weights of GWP, AP, HTP, and ADP were 0.482, 0.272, 0.158, and 0.088, respectively.

6 Results and discussion

6.1 Process contribution

Two major components mainly contribute to the environmental effect: the Pidgeon process and ferrosilicon production. The greater or lesser impact of each of these two components varies depending on the category of impact that has been valued, while, in general, their contribution takes over 80% of the overall impact for each category. The percentage of environmental impact associated with each component category can be seen in Fig. 2.

In the case of the Pidgeon process, the largest environmental impact is determined by the amount of fuels used. The impact is accentuated by the amount of the reducing agent and catalyst used. The emission of CO_2 from scenario 2 was increased although the PG was used as the major fuel and aggravated considering the burden of PG production.

In the case of the production of gaseous fuels, the greenhouse gas emission from COG was 2.5% more than that from PG. However, its final impact was decreased because of the reduction of the amount of COG and higher calorific value used in the Pidgeon process.

In the case of ferrosilicon production, the direct emissions of CO_2, SO_2, and PM10 were obtained from published literature (Zhou 2001) of previous research, but the key element is the emissions from electricity consumed, which we defined as indirect emissions in its manufacture. Considering the contribution of electricity consumption, a significant reduction in the environmental impact of Fe–Si production is possible by converting from coal-based to gas-based electricity or hydropower.

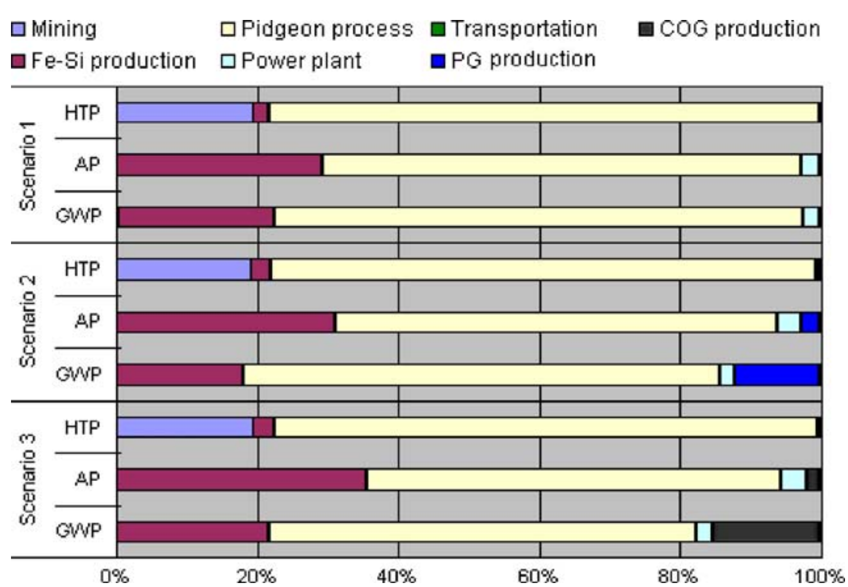


Fig. 2 Process contribution of each scenario per impact category

Table 5 The characterization results of the three scenarios

	GWP kg CO_2 eq	AP kg SO_2 eq	HTP kg 1,4-DCB eq	ADP kg antimony eq
Scenario 1	3.66E+04	2.92E+02	4.57E+03	4.90E+01
Scenario 2	4.19E+04	2.52E+02	3.24E+03	3.44E+01
Scenario 3	3.41E+04	2.17E+02	3.04E+03	3.27E+01

6.2 Environmental impact

The characterized results of the three scenarios were listed in Table 5.

- ADP: The mineral categories of magnesium production mainly include dolomite, fluorite as well as silica and iron ores which are used for producing ferrosilicon, while the energy categories mainly include coals and electricity. The electricity will be converted into the consumption of primary energy sources, such as coal, petroleum, and natural gas, on the basis of the life cycle inventory of China's electricity generation (Di et al. 2007). The characterization factors of energy categories, due to the abundant reserves, were comparatively less than that of mineral categories, so its impact on the cumulative consumption of resources can be neglected. Because of the reduction of dolomite in scenarios 2 and 3, ADP in these two scenarios dropped to 30% and 33%, respectively, than scenario 1.
- GWP: CO_2 was the major gas to cause greenhouse effect in Mg production, and CH_4 was mainly from the gaseous fuels production and power plants providing the electricity to the processes. GWP in scenario 2 was 14% higher than that of scenario 1, while GWP of scenario 3, which used COG as major fuel for magnesium production, decreased by 7% than that of scenario 1. It showed that there was no apparent effect from the practice of adopting PG as major fuel for Mg production so as to reduce global warming potential. Scenario 3 can effectively reduce global warming potential, but magnesium-smelting plants need to be constructed near the coke plant, and the choice of the location was restricted. From scenarios 1 to 3, GWP of the Pidgeon process, respectively, accounts for 68%, 70%, and 64% in their accumulative GWP. Therefore, the Pidgeon process was the crux of controlling greenhouse gas emissions. The amount of emissions from the processes of dolomite extraction and transportation was very small, accounting less than 0.5% in the cumulative GWP.

Since the 1970s, sulfur hexafluoride (SF_6), a potent greenhouse gas with a high global warming potential, has been commonly used for the protection of melted magnesium. Recently, the promotion of measures has been made to limit the use of SF_6 to prevent global warming under the Kyoto Protocol in some regions (Europe, Japan, etc). In China, most magnesium plants use sulfur or fluxes containing small amounts of sulfur for preventing the magnesium melt from burning since the cost of SF_6 is much higher than sulfur and other protection agents. Actually, magnesium alloy producers in China use SF_6 mixed with CO_2, N_2, and/or SO_2 to prevent oxidation and burning of the melted metal. The estimated amount of SF_6 used varies in an uncertain range of 2.5–5.0 kg/tons Mg–alloy ingot through investigation of magnesium alloy plants.

- AP: The gases that contribute to acidification were mainly SO_2 and NO_X. SO_2 was mainly emitted from the Pidgeon process, especially the dispersed sulfur oxidized over molten magnesium surface with high temperature (about 720°C), as well as the indirect emission from the Fe–Si production. HF from catalyst used in the reduction process was another type of gas contributing to acidification. The SO_2 and NO_X emission decreased with the reduction of the direct consumption of coal. The processes of gasification and coking of coal would help in the reduction of SO_2 and NO_X emissions (Wu and Chen 2001; Guo et al. 2005). Total accumulative reductions of 14% and 26% were obtained for scenarios 2 and 3, respectively.
- HTP: The emissions contributing to this impact category were mainly SO_2, NO_X, HF, and PM10. For the three scenarios, the large environmental threat to human health was HF from the Pidgeon process by reduction, taking an average of 73% in the cumulative HTP. Total cumulative reductions of 29% and 33% were achieved for scenarios 2 and 3, respectively.

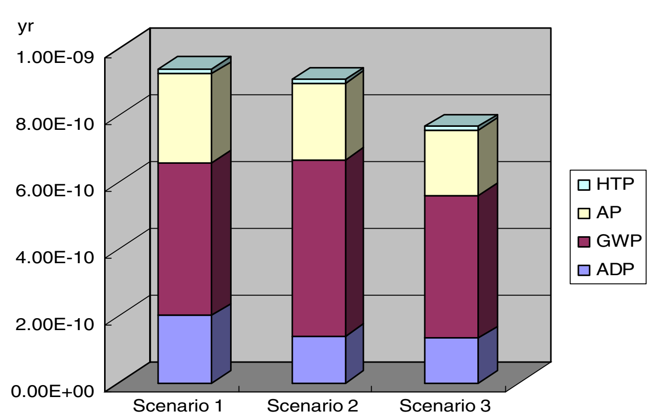


Fig. 3 Final single results for the three scenarios

6.3 Final results

The final single results of scenarios 1 to 3 were 9.40×10^{-10}, 9.07×10^{-10}, and 7.68×10^{-10} year, respectively. The results indicated that the accumulative environmental performance of adopting scenario 3 to produce primary magnesium was relatively lowest; scenario 2 comes next and had a 18% increase than scenario 3, and scenario 1 showed the highest accumulative environmental load and had a 22% increase than scenario 3. Figure 3 illustrated the absolute values of each impact category of the three scenarios, which showed that GWP and AP were the major impacts of Mg production. Concerning the Pidgeon process, the impact of abiotic resources depletion deserves more attention although the types and the amount of mineral resources for Mg production are abundant in China.

The different fuel use strategies in the practice of magnesium production using the Pidgeon process caused much different results on accumulative environmental performance. The life cycle environmental performance of scenario 3, which adopts the local production networks of coke–ferrosilicon–magnesium, was the best even if the emissions of COG production were considered. But scenario 1, which burns coal directly as overall fuel, showed poor environmental performance. This means that a positive improvement can be achieved through the integrated production of several commodities. Considering that the COG was limited by gas supply conditions and the location of magnesium plants, PG, in areas where coke production was not concentrated, could be used as the major fuel for primary magnesium production.

7 Conclusions

This study, according to the LCA procedure, based on the scenarios of three different fuel use strategies, carried out environmental impact assessment on the practice of magnesium production with the Pidgeon process in present China. The system assessed, which is from the dolomite ore entering the system to ingots of primary magnesium leaving at the gate, has been considered as a representative system of the magnesium industry in China. The data on the three scenarios are based on the current practice of magnesium production, and the results may be useful for environmental assessment of primary magnesium ingots produced in China. The emissions inventory showed that both the Pidgeon process and Fe–Si production were mainly to blame for the pollutant emissions in the life cycle of magnesium production. The characterized results indicated that ADP, AP, and HTP decreased cumulatively from scenarios 1 to 3, with the exception of GWP. The final single scores displayed that the accumulative environmental performance of scenario 3 was the best compared with scenarios 1 and 2. This study suggested that PG was an alternative fuel for magnesium production rather than coal burned directly in areas where the cost of oven gas-produced coke is high. The utilization of “clean” energy and the reduction of greenhouse gases and acidic gases emission were the main goals of the technological improvements and cleaner production of the magnesium industry in China.

Although there were some limitations in the assessment method of “from cradle to the gate” which this case study adopted, this paper has demonstrated that the theory and method of LCA actually have extensive application value for the research on the environmental performance of primary magnesium production.

8 Future work

In this work, the environmental performances of primary magnesium production were analyzed based on a “cradle-to-gate” LCA approach. However, a full LCA study would incorporate a “cradle-to-cradle” scheme. Future work will focus on the study of the production of main magnesium alloys, product use, and end-of-life phases, including recycling and re-use.

In addition, other energy sources such as natural gas and coal–water slurry used in magnesium production would be treated in further research. The cost of energy production could be taken into account to provide an understanding of how economically viable it is to implement environmental management.

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